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THE USE OF THE LANGMUIR PROBE TO DETERMINE ELECTRON DENSITIES SURROUNDING RE-ENTRY VEHICLES

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

CONTRACT NAS1-2967

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STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

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ABSTRACT

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An experimental investigation of the operation of electrostatic probes in a flowing plasma was carried out to determine the operation of such probes when the probe radius is comparable to, or larger than, the mean free path. The investigation was carried out in an electromagnetic shock tube capable of producing plasma flows greater than 1 cm/μsec and electron densities greater than 10^{14} electrons/cc. Measurements were made at pressures from 0.040 to 0.200 mm hg. When the electron density was below 10^{12} electrons/cc a 9-Gc microwave transmission system was used to check the electron density measured by the probes. Shock velocity was measured with a microwave Doppler system.

The voltage applied to the probes was sinusoidally varied at a 100 kilocycle rate, so that electron temperature and electron density could be obtained from the current-voltage characteristics.

Probe results were compared to the microwave results and to each other. Good agreement was obtained between the microwaves and the probes as well as between probes, even when the mean free path was one-fifth the probe radius. All probe data were interpreted using free molecular theory.

A simple theory accounting for the change in current collection when a cylindrical probe is perpendicular to a directed flow was verified within the experimental uncertainties.

Author

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I INTRODUCTION

The determination of the electron density surrounding a re-entry vehicle from gas-dynamic calculations is hampered by uncertainties in the rate constants of the ionization processes, as well as by the effects of ablation products. However, calculations have been made for ionization in air (i.e., with no ablation products) and it would be desirable to be able to check them with flight-test data.

One common method of determining electron density is to use microwave techniques to measure various combinations of attenuation, phase shift, and reflection coefficient of a plasma. However, these measurements given only limited information. The measurement gives only an integrated effect of the plasma upon the microwave property that is studied. In order to interpret the results in terms of electron density and collision frequency, it is necessary to estimate the spatial distributions of these parameters, although the spatial distribution is itself one of the parameters that one would like to obtain from the measurements. In addition, the dynamic range of parameters that can be measured by such methods in a realistic flight test is usually quite small. It is usually possible to determine the electron density only when the plasma frequency is of the order of the microwave frequency. When the plasma frequency is much greater than the microwave frequency, the attenuation becomes too large to measure and the reflection coefficient becomes insensitive to the actual value of the electron density. If the plasma frequency is much below the microwave frequency, the effect of the plasma becomes undetectable.

An alternative technique for measuring the electron density during flight tests is to use an electrostatic probe (Langmuir probe). It is possible to design these probes so that measurements can be made with a spatial resolution of less than 1 mm. Thus, using a probe that could move radially outward from the re-entry vehicle, it would be possible to determine the spatial distribution of electrons. Alternatively, one could use several probes mounted at different radial distances from the vehicle surface.

Langmuir probes are inherently capable of measuring a wide range of electron densities. Roughly speaking, the electron density is proportional to the saturation ion current, so that all that is needed to measure a change of electron density of three orders of magnitude is a current-measuring device with the same dynamic range. These are available in forms that present the current variation either linearly or logarithmically.

From the foregoing discussion, it seems clear that probes are worthy of consideration for use in flight tests. Probe theory, however, is predicated on a number of conditions that will not hold true over the entire trajectory of a vehicle. The most important condition usually assumed is that of free molecular flow. It is necessary to determine the errors involved in the inferred plasma parameters when this condition does not hold and to develop a theory that will enable one to interpret the data over the complete trajectory.

Another effect generally not considered in laboratory studies using probes is the effect of a directed velocity. If the probe is mounted perpendicular to the velocity vector, the electron flux collected by the probe will be increased. In order to minimize this effect, cylindrical probes could be mounted so that their axes were parallel to the velocity vector. However, because the re-entry vehicle may oscillate about the velocity vector, it may be impossible to ensure that the probe axes are parallel to the velocity vector. It is therefore, important to understand what effects the directed velocity may introduce into the interpretation of the probe data. Some theoretical work has been done in this area, but usually the assumption is made that the sheath is not altered by the flow and that free molecular conditions hold.

Some experimental work has been done at this laboratory with Langmuir probes in shock tubes, as well as in a variety of other plasmas.[1*] Fixed bias voltages were used so that the entire current-voltage characteristic was not obtained. Because of this, no temperature measurements were possible. However, by estimating the temperature, and using this value to obtain a value for the electron density, it was possible to evaluate

*References are listed at the end of the report.

the operation of probes and to compare them to microwave transmission measurements. The results of such measurements were encouraging enough to warrant a more thorough investigation.

This report describes the start of a program to investigate the use of probes where free molecular conditions do not hold and where directed velocity effects may be significant. The work was carried out in an electromagnetic shock tube, which is an excellent tool for such a program because of its rapid rate of fire.

II EXPERIMENTAL APPROACH

We shall not develop the theory of probe operation in free molecular flow in this section, since it is well documented in the literature for both equal area and unequal area probes of a variety of shapes.[2-6] However, we shall discuss some of the characteristic dimensions of importance in this theory so that we can estimate what experimental conditions it will be necessary to obtain in order to ensure that free molecular theory no longer applies.

A. MEAN FREE PATH CONSIDERATIONS

The three characteristic dimensions of importance are the mean free path, λ, the Debye length, λ_d, and the probe radius, r_p. For free molecular flow, it is necessary that the mean free path be much larger than both the Debye length and the probe radius. The sheath thickness is of the order of several Debye lengths, so that if the mean free path is much larger than the Debye length, there will be no collisions in the sheath. If the mean free path is much larger than the probe radius, the disturbance of the plasma by the presence of the probe will be small.

Let us consider to what extent we may vary these three parameters. A wide range of probe radii are available to us, ranging from a minimum of about one mil up to as large as is desired.

The Debye length is given by the expression

$$\lambda_D = 7\sqrt{T/n} \quad \text{cm}$$

where T is in degrees Kelvin and n is in electrons/cc. Thus the Debye length is determined by the plasma properties. By firing the electromagnetic shock tube at different voltages, and by waiting different lengths of time after the shock passage, a wide range of Debye lengths can be obtained. Equation (1) is plotted in Fig. 1.

If the mean free path is mainly determined by collisions between ions and neutral gas species, then it may be varied by varying the pressure. This can be done over a rather limited range with the electro-

$$\lambda_{e-n} = 1.55 \times 10^{-5}/\rho/\rho_o \quad \text{cm}$$

From kinetic theory[8] the ion-neutral mean free path is $1/4\sqrt{2}$ times the electron-neutral mean free path. Further, because of the small electric field that exists outside the sheath, the ions have a velocity associated with a temperature 2T rather than T. Introducing these factors, the ion-neutral mean free path is

$$\lambda_{i-n} = 1.55 \times 10^{-3}/\rho/\rho_o \quad \text{mils.}$$

This equation is plotted in Fig. 2. If collisions between charged particles become significant the mean free path will be even smaller. The mean free path for ion-ion and electron-electron collisions is shown in Fig. 3.

Deviations from the free molecular case may occur for various combinations of the three characteristic dimensions. If the mean free path is not much greater than the probe radius, the free molecular assumptions are not strictly valid.

<u>Case 1</u>

$$r_p \geq \lambda$$
$$\lambda \gg \lambda_D$$

Under this conditions, the free molecular assumptions are not strictly valid. But since the mean free path is much greater than the Debye length, there will be no collisions in the sheath. The area of the sheath will be approximately equal to the area of the probe.

<u>Case 2</u>

$$\lambda_D \geq \lambda$$
$$r_p \gg \lambda_D$$

In this case there are collisions in the sheath and the free molecular assumptions are not strictly valid. If the tube is operated at a pressure of about 30 to 40 microns, at which it works best, the ion-neutral mean free path in the ambient gas is about 25 mils. In the shock compressed gas behind the front, where the density is at least an order of

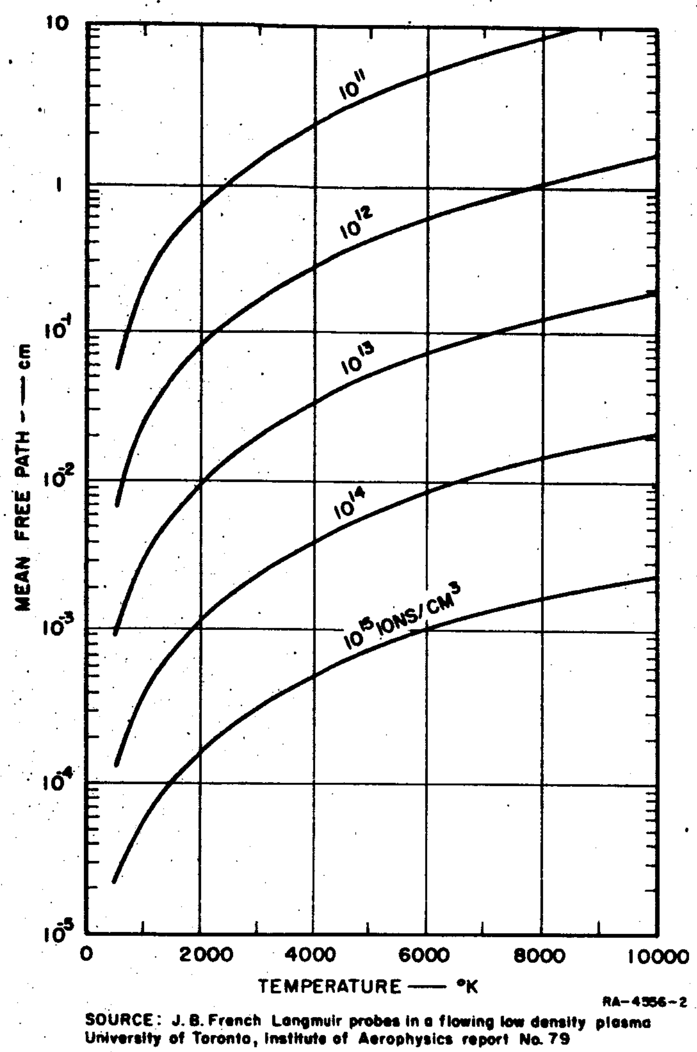


FIG. 2 ION-NEUTRAL MEAN FREE PATH AS A FUNCTION OF ρ/ρ_0

magnitude greater, the ion-neutral mean free path is less than 3 mil. Thus, by making measurements with a series of probes of increasing radii in the range of a few mils up to greater than 25 mils, it should be possible to transition from the free molecular to the continuum region. By operating the tube at pressures up to a few hundred microns, measurements well into the continuum region should be possible.

For a given probe radius and mean free path the difference between Case 1 and Case 2 may be explored by working with different electron

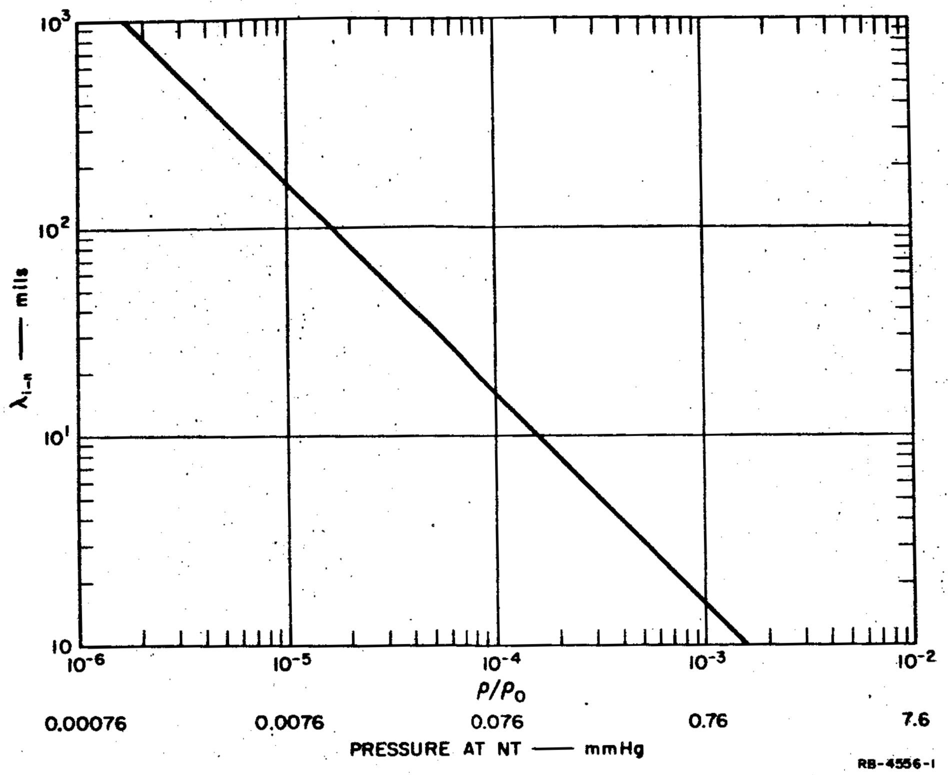


FIG. 3 ION-ION AND ELECTRON-ELECTRON MEAN FREE PATHS AS A FUNCTION OF TEMPERATURE FOR DIFFERENT CHARGED PARTICLE DENSITIES.

densities. For very high electron densities the conditions of Case 1 will hold, while for lower electron densities Case 2 will be obtained.

Because probe operation is well understood for free molecular conditions, it was thought advisable to operate one probe under these conditions and compare the results obtained from it with those obtained simultaneously from a probe operating under conditions of Case 1. In this way deviations in the probe results could be evaluated on a single shot of the electromagnetic shock tube. Variations from shot to shot would not have to be considered. Once the uniformity of the shock was established, any other differences between the two probes could be attributed to the probe operation.

This scheme will not work for Case 2, since the simple Langmuir theory does not handle the case of collisions in the sheath.

B. MICROWAVE CHECK

An over-all check on the probe operation through the use of a microwave transmission measurement was thought advisable. This could also serve as a check on the probe circuitry to ensure that it was operating properly. An X-band (f = 9 Gc) phase and attenuation system was used for this purpose. It will be described in a later section.

C. SHOCK FRONT VELOCITY MEASUREMENT

Data have been gathered on the shock velocity as a function of position down the tube for some conditions of shock voltage and pressure. These measurements were made with photomultipliers and required a considerable amount of time and data channels to explore a variety of conditions. A Doppler system, on the other hand, is capable of giving a complete record of velocity of the shock front as a function of position on a single shot. Therefore, a simple Doppler system was set up to measure shock velocity. It is described in the next section.

III DESCRIPTION OF THE EXPERIMENTAL SETUP

A. ELECTROMAGNETIC SHOCK TUBE

For the studies in which the directed velocity was not of interest, less exotic (i.e., dc discharges or RF discharges) techniques than electromagnetic shock tubes could have been used to produce the plasma. In fact, the shock tube does have the disadvantage of being a transient device, so that high-speed instrumentation had to be developed to gather the data. All data are taken from photographs of oscilloscope traces. But in addition to its use as a device for producing a high-velocity plasma, which was necessary for the velocity studies, the shock tube has the further advantage of producing thermal plasmas. The ionization in the shock front does not depend upon accelerating electric fields. This is an important consideration in a study in which the probe is to be made very large compared to the mean free path, since a large probe might not only have different current-gathering characteristics than smaller probes, but in an electrically produced plasma, the probe may alter the ionization processes. In dc discharge, the probe may become one of the electrodes in the discharge process, while in RF discharge the presence of the probe may alter the electric field in its vicinity and so alter the ionization around the probe.

Since the plasma of direct interest for the purposes of this study is the flow field around a re-entry vehicle, in which the ionization is produced thermally, the shock tube was judged best able to reproduce this plasma, and it was decided to use the shock tube for all of the studies.

The electromagnetic shock tube has two advantages over the conventional pressure-driven shock tube: A much higher rate of fire and more easily produced high-velocity shock. However, one pays for these advantages by knowing considerably less about the state of the shock gas than in a pressure-driven tube. For this initial study, however, the rapid rate of fire of the electromagnetic tube is especially important, because a great number of shots are necessary in the development of adequate instrumentation. It would have been impossible in the short time available to this program to develop the instrumentation that was developed if a pressure-driven shock tube had been used.

In the electromagnetic shock tube there is no diaphragm separating a high-pressure and low-pressure regions to be burst. Rather, high-pressure hot gases are produced in the driver section by a discharge and then accelerated out of this region by a pinch. A schematic of the discharge assembly in which the shocks are produced is shown in Fig. 4. The device is patterned after Josephson's axial discharge system.[9] The discharge section consists of a tapered glass tube with a solid electrode at the small end and a ring electrode at the large end, where the cylindrical tunnel begins. The discharge occurs in the tube when the switch is activiated and the condenser bank is connected across the conical section through the coaxial ground return. After the gas breaks down, the large current causes a pinching of the ionized gas. Because of the geometry, the pinching occurs at the small end first. The pinching process progresses along the tapered section to the hollow electrode, with the resulting hot plasma mass driving a high-velocity shock into the cylindrical test section.

The switch between the condensers and the central electrode is activiate by reducing the pressure in the switch section until breakdown occurs.

The 30-μfd capacity condenser bank has a voltage rating of 20 kv. The condensers, charging power supply, and appropriate switch gear are contained within a metal box.

The tube proper is a 15-cm ID Pyrex pipe. Its length is varied by adding or subtracting sections of pipe. For the experiments reported in this study, the tube was about six feet long. Measurements are made by introducing the instrumentation through ports in the side arms of Pyrex crosses. Photomultiplier measurements are generally made by making observations through the glass walls.

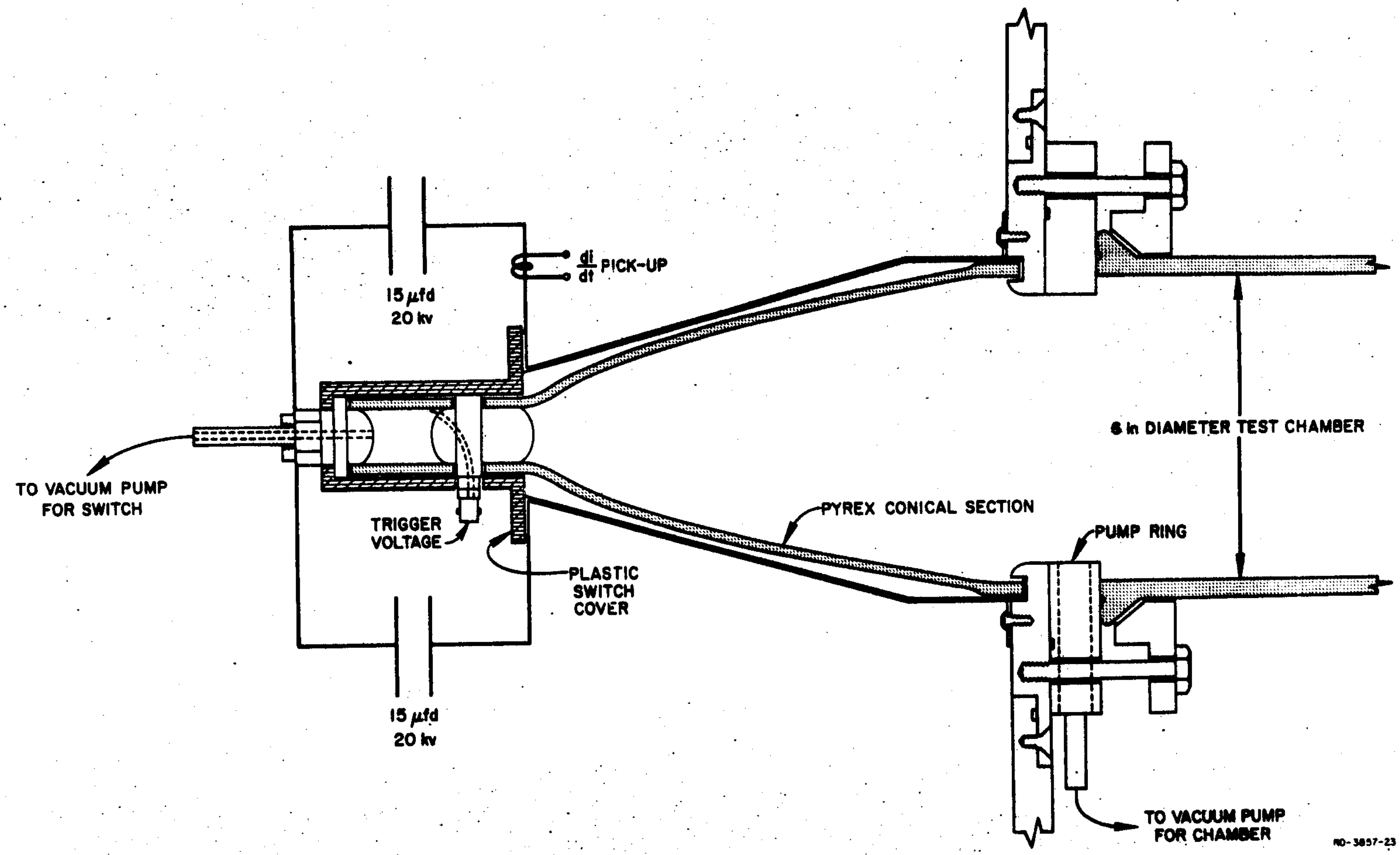


FIG. 4 DETAIL OF THE CONICAL DISCHARGE SECTION

B. PROBE MOUNTING IN THE SHOCK TUBE

In order to make measurements in as uniform a region of the shock as possible, the probes were mounted on a brass plate that was inserted halfway across the shock tube. The probes were mounted symmetrically about the center line of the plate, with a center-to-center spacing of 1 in. The probes and mounting holes were designed so that different probes could easily be mounted or changed about as the experimental conditions demanded. The microwave antenna was mounted 1-5/16 in behind the probe mounting holes, because there was not room to mount both the probes and the microwave antennas at precisely the same station without separating the probes more than was desirable. This displacement of the microwave antennas and probes accounts for about 5 microseconds of time difference in the two systems.

The other microwave antenna was mounted in one of the side arms just outside the inner diameter of the shock tube. The spacing between the antennas was 3 in.

In order to minimize lead capacitance, the probe transformers were mounted in the shock tube, just behind the brass mounting plate. The sweeping circuitry will be described in more detail in a later section.

A sketch of the mounting of the probes and microwave antennas is shown in Fig. 5.

C. SHOCK TUBE INSTRUMENTATION

1. General

A variety of measurement techniques have been used in conjunction with the shock tube, including microwave transmission measurements, photomultipliers, pressure transducers, magnetic probes, electrostatic probes, Doppler measurements, and image-converter photography. For this study, the microwave transmission, Doppler, and electrostatic probe techniques were used almost exclusively.

2. Microwave Transmission System

In order to determine the electron density and collision frequency of a plasma, it is necessary to make two independent measure-

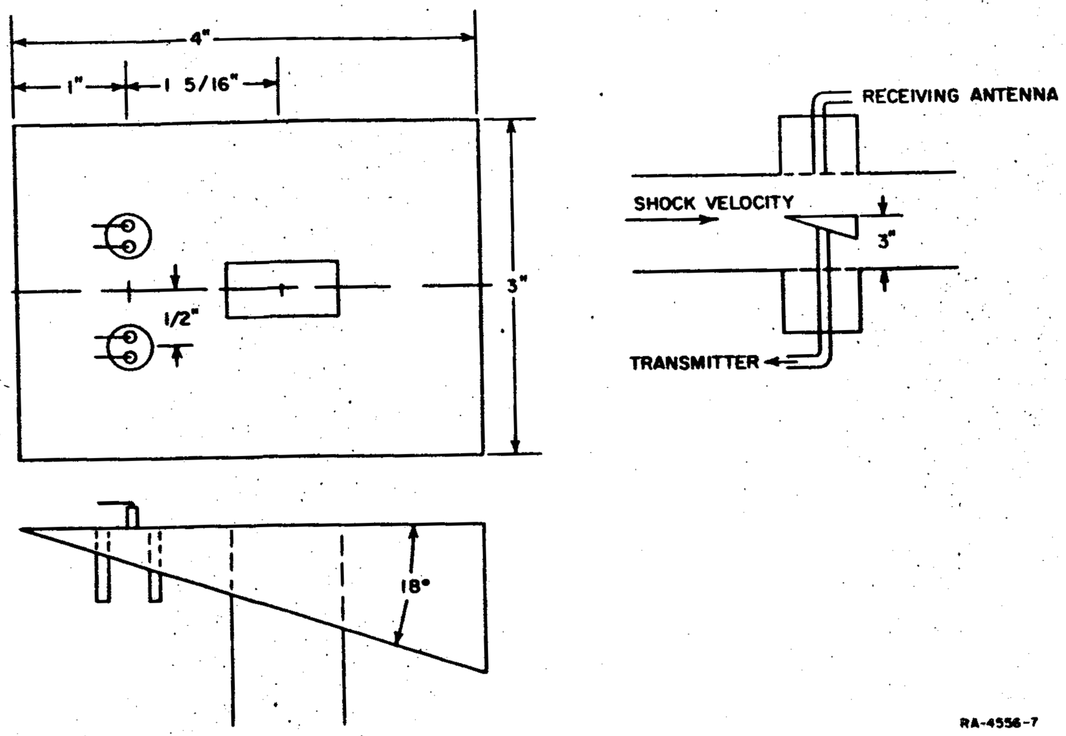


FIG. 5 LAYOUT OF MOUNTING HOLES FOR THE PROBES AND THE LOCATION OF THE MICROWAVE ANTENNA

ments. Very often this is performed by measuring the absorption and phase shift, at a single frequency, of an electromagnetic wave that is transmitted through the plasma. By constructing a bridge circuit in which the plasma is one arm and a calibrated phase shifter and calibrated attenuator are another arm, a sensitive instrument for measuring absorption and phase shift can be made. In this system, in order to null the bridge, both the attenuator and phase shifter must be adjusted before either the phase shift or attenuation of the plasma can be determined. The phase shift cannot be found independent of the attenuation.

A conventional bridge circuit, such as the one described above, can not be used for measurements on the shock tube because of the short times involved. It is desirable to be able to measure continuously with a resolution time of the order of microseconds. In order to adapt the conventional bridge for use with the shock tube, it is necessary to add servo loops to control the phase shift and attenuation in one arm of the bridge.[10] However, because of limited time and funds on this study, a simpler system was used, which could be improved at a later date if time and funds were sufficient. This system operates in such a manner that a null can be obtained in the phase-measuring system that does not depend upon the amplitude of the signal that has passed through the plasma. Thus, if phase shift information only is desired, which is the case when only electron density is of interest and the ratio of collision frequency to radian radio frequency is less than a few tenths, a servo loop is needed only on the phase shifter. When the system is not provided with a servo loop, the output voltage is a sinusoidal function of the phase shift and is independent of the amplitude variation of the signal through the plasma if it is sufficiently small. If the amplitude variations are large, the output voltage must be calibrated in terms of plasma attenuation and the plasma attenuation measured as a function of time.

The basic system is shown in Fig. 6(a). A klystron oscillator supplies microwave power, which is divided in a directional coupler between a path that goes through the plasma (Path A) and a path that does not (Path B). The two signals are recombined in a magic tee. As shown in Fig. 6(b), when the two signals are 90 degrees out of phase, the resultant fields in the crossed arms of the magic tee, $|E_1|$ and $|E_2|$, are equal. The important point to note is that this is true regardless of the relative amplitudes of the signals that have traveled along Path A and B. If, with no plasma between the antennas along Path A, the voltage difference between $|E_1|$ and $|E_2|$ is adjusted to zero by adjusting the phase shifter, we can be certain that the input signals to the magic tee are in phase quadrature. When a plasma is introduced between the antennas the phase along Path A changes and the voltage difference between $|E_1|$ and $|E_2|$ will no longer be zero. The phase shift introduced by the plasma can be determined by adjusting the phase shifter until the voltage difference between the crossed arms of the magic tee is again

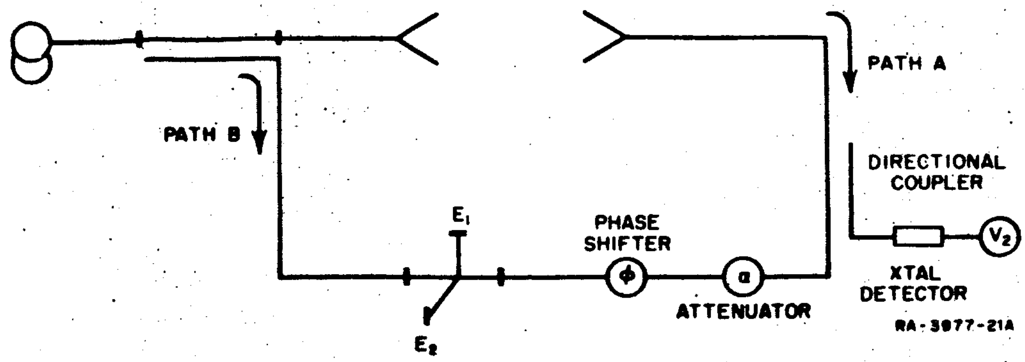


FIG. 6a MICROWAVE SYSTEM FOR THE INDEPENDENT MEASUREMENT OF ATTENUATION AND PHASE SHIFT

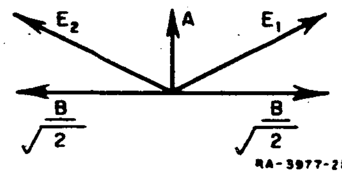


FIG. 6b VECTOR DIAGRAM OF VOLTAGE AT OUTPUT TERMINALS OF THE MAGIC TEE

zero. The amount of phase shift that is added by the phase shifter is equal to the phase shift introduced by the plasma.

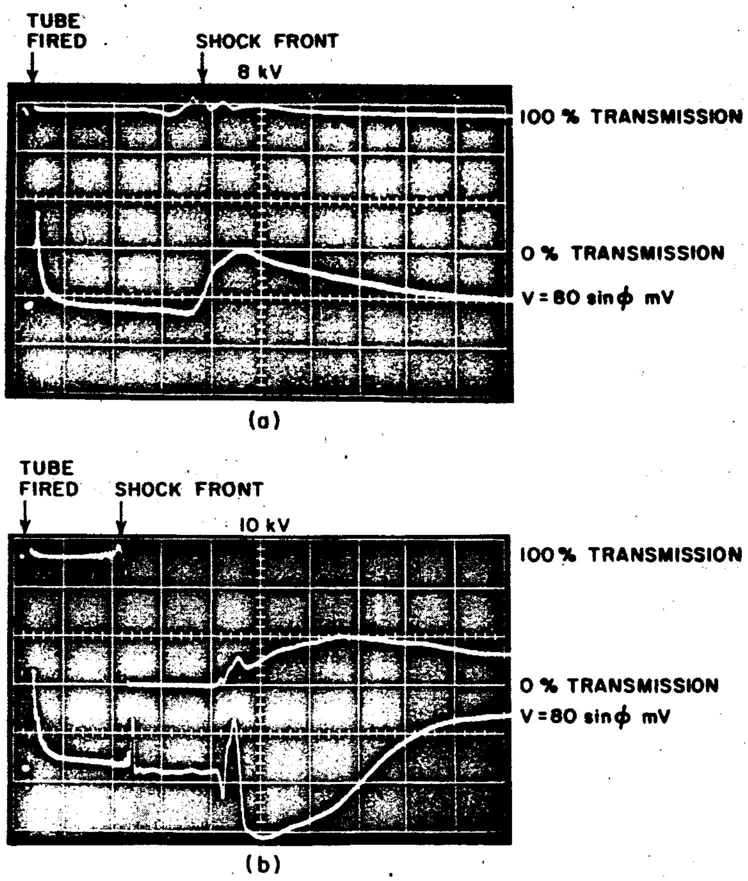
With the system operating as a null device, the voltage difference between the crossed arms of the magic tee would act as an error signal to drive a servo loop, which in turn would adjust the phase shift until a null in the voltage difference was obtained.

If, instead of adjusting the phase shifter so that the voltage difference between $|E_1|$ and $|E_2|$ goes to zero we measure the voltage difference, we shall get a measure of the phase shift introduced by the plasma. This is the manner in which the system was operated for this study. Calibration curves were taken for voltage difference as a function of phase shift for different attenuation settings. The system was set at zero voltage difference before the shock tube was fired. Then, as the shock entered the region between the antennas, a phase shift was introduced and the voltage varied in accord with it. After the shock has passed, the electron density decays and the voltage varies in accord with this variation of electron density.

Since the voltage difference will be the same for a phase shift of Φ degrees and $\Phi \neq 2\pi n$ (where n is an integer) the value of the phase shift can not be determined from the instantaneous voltage alone. Ambiguities in phase can be resolved by waiting long enough so that the electron density produced a phase shift of less than 90 degrees. Then the phase shift at earlier times can be traced out from the oscillograph of the voltage difference.

Some examples of phase shift and attenuation for different cases are shown in Fig. 7. In Fig. 7(a), a relatively low shock voltage was used and the measurements were made sufficiently far down the tube so that only a weak shock remained. When the tube is fired, the tube is ionized by a process that is still uncertain but may be photoionization or X-ray ionization. This ionization is detected by the microwaves at the extreme left of the photographs. This ionization decays to a great extent before the shock arrives at a time of about 350 microseconds. The phase shift decreases when the shock arrives and decreases to a minimum of about 55 degrees in this case, at which time the electron density begins to decrease. The attenuation during the shock passage is less than 0.5 db.

In Fig. 7(b), a relatively strong shock voltage was used. Once again the effects of the ionization produced when the tube is first fired are detected by the microwave system. The shock has a greater velocity than in the previous shot and so arrives at the same station at an earlier time. However, now the electron density is great enough to produce changes in phase shift greater than 360 degrees. The electron density was greater than critical and the microwaves suffered so much attenuation that both the phase and attenuation channels indicated essentially zero signal. After the shock passage, the electron density began to decay. When it had decayed to about 10^{12} electron/cc, the microwave system was able to follow the variation in phase shift. Using



PRESSURE = 0.040 mm Hg
FREQUENCY = 9 Gc
STATION – 160 cm FROM RING ELECTRODE
UPPER CHANNEL – ATTENUTION, 5 mV/cm
LOWER CHANNEL – PHASE SHIFT, 50 mV/cm
SWEEP SPEED = 100 μsec/cm

RA-4056-16

FIG. 7 PHASE SHIFT AND ATTENUATION OF A 9 Gc SIGNAL AS A FUNCTION OF TIME the method discussed above of counting phase shift from the 90 degrees point and then noting the phase shift at earlier times, we can see that the phase shift was 180 degrees at 700 microseconds, 270 degrees at 500 microseconds, 360 degrees at 440 microseconds, and 450 degrees at 425 microseconds. The corresponding electron densities, assuming a uniform slap of plasma are 3.6X10", 5.1X10", 6.4X10" and 7.5X10" electrons/cc.

3. Doppler Measurement of Shock Front Velocity

There exist a variety of methods for measuring the velocity of the shock front. The shock front marks a rapid transition in the value of the temperature, density, pressure, electron density, and light output. Thus, probes spaced a known distance, which can detect changes in the value of any of these parameters, can be used to measure velocity by simply measuring the time it takes for the rapid transition to travel the known distance. An example of such a device would be a pair of photomultipliers spaced 10 cm apart. If the output of each photomultiplier is recorded on an oscillograph, the time between the rapid rise in output voltage for the two photomultipliers can be measured. The velocity is then 10 cm divided by the time measured between outputs. This technique gives the average velocity over the time interval, so that for accurate measurements of the velocity at a given station down the tube, the spacing between the sensors should be small.

This technique, while relatively simple and capable of good accuracy, requires a number of oscilloscope channels if the velocity down the tube is to be monitored at a number of stations on each shot. An alternative technique that gives a continuous record of velocity and using only one oscilloscope channel was developed for this study and is described below.

If a microwave signal is transmitted from an antenna and scatters off a stationary obstacle it will be detected at the receiver with some fixed phase difference with respect to the transmitted signal. If the scattering obstacle is moving with some radial component with respect to the receiving antenna, the received signal will have a time-varying phase and will appear as a shift in received frequency compared to the transmitted frequency. Thus, by measuring the shift in received frequency, the radial velocity of a target can be measured. The frequency shift is called the Doppler shift.

This phenomenon can be adapted to a technique for measuring the shock front velocity. The shock front is marked by a rapid rise in electron density. If a microwave signal of frequency less than the plasma frequency is transmitted down the tube, it will be reflected off of the shock front at a point in the front located approximately at the position at which the microwave frequency is equal to the plasma frequency. The received microwave signal will be Doppler-shifted an amount equal to

$$\Delta f = 2\, v/c\, f_o \quad ,$$

where Δf is the Doppler frequency

v is the velocity of the point of reflection; nominally the front velocity

c is the speed of light in the medium

f_o is the microwave transmitted frequency.

A schematic diagram of the system is shown in Fig. 8. A signal generator operating at 10 Gc with a power output of about 1 milliwatt

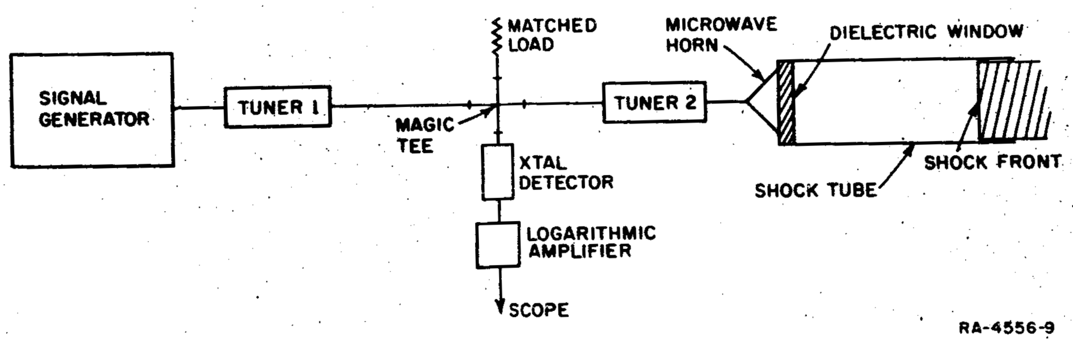


FIG. 8 SCHEMATIC DIAGRAM OF THE DOPPLER SYSTEM

was used as a transmitting source. This fed power to a microwave horn that was placed so that it radiated power down the shock tube. A tuner placed before the antenna was used to adjust the level of reflected signal available at the detector that was connected to the magic tee. This fixed amount of reflected signal mixed with the reflected signal that was returned from the scattering by the shock front. The mixing was accomplished in the crystal detector. The output of the detector contained signal at both the sum and difference frequencies of the frequency components at the detector input. Since the frequencies at the input were f_o and $f_o + \Delta f$, the detected frequencies were $2f_o + \Delta f$ and Δf. The upper frequency is filtered out in the detector, so that the output consists only of the Doppler frequency. The amplitude of this component is proportional to the product of the amplitude of the fixed reflection and the time-varying reflection. Since the range to the varying reflection changes as the shock progresses up the tube, the amplitude of the Doppler component also changes with time. At times just after the shock emerges from the discharge section, the range is so great that the reflected signal amplitude is very low, while when the shock arrives near the end of the tube, where the antenna is located, the range is so small that the reflected amplitude is very great. These amplitude variations were reduced by inserting a logarithmic amplifier between the detector output and the oscilloscope.

The setting of the tuners deserves some mention. If Tuner 2 were adjusted for a perfect match, there would be no fixed reflected signal at the detector for the scattered signal to beat with. There would be no beat frequency. If the tuner were adjusted for a perfect mismatch, all of the power incident on the tuner would be reflected and no signal would reach the shock front. Again there would be no beat frequency. Thus, Tuner 2 must be adjusted midway between a perfect match and a perfect mismatch. This was done by using a pickup horn part way down the tube to monitor the transmitted signal. The tuner was adjusted for a maximum at the pickup horn. Under this condition, the reflected signal was very low. Then the tuner was backed off until the signal at the pickup horn was 3 db below the maximum. At this point, half of the available power was being transmitted and half was being reflected at Tuner 2. Then Tuner 1 was adjusted for maximum transmitted power.

Some typical data obtained with this system are shown in Fig. 9. There is some irregularity in the frequency pattern due to reflections from the glass walls of the tube and the metal flanges that are used to fasten sections of the tube together. Nevertheless, the Doppler frequency is clearly discernible. When the shock first emerges from the discharge section, it is moving very rapidly and then begins to slow down as it moves down the tube. The rate of decay is greater than for a pressure-driven shock tube, since there is no reservoir of high-pressure gas. This decay in shock velocity is seen from the decrease of Doppler frequency with time.

When the tube is first fired, as mentioned before, the entire tube is ionized almost instantaneously. In the cases shown, the level of ionization was great enough to attenuate the microwave signal strongly before it reached the emerging shock front. The signal was also reflected due to the plasma produced in the tube close to the antenna. This shows up on the oscillographs as a displacement in the detected signal that varies slowly with time. The slow time variation corresponds to the decay of the precursor ionization. When the precurosor ionization becomes low enough, the microwave signal is able to reach the shock front with strength sufficient for it to be scattered and detected. This scattered signal then mixes with the fixed reflection to produce a sinusoidal output, which varies with a frequency equal to the Doppler frequency.

The results for a series of shots at shock voltages of 8, 9 and 10 kv are shown in Fig. 10. As is expected, the shock front velocity increases with shock voltage. The range over which useful data were obtained was about 70 cm. One phenomenon to be noticed from these data is that as the range from the antenna to shock front increased the shock velocity also increased, but that this increase levelled off at ranges

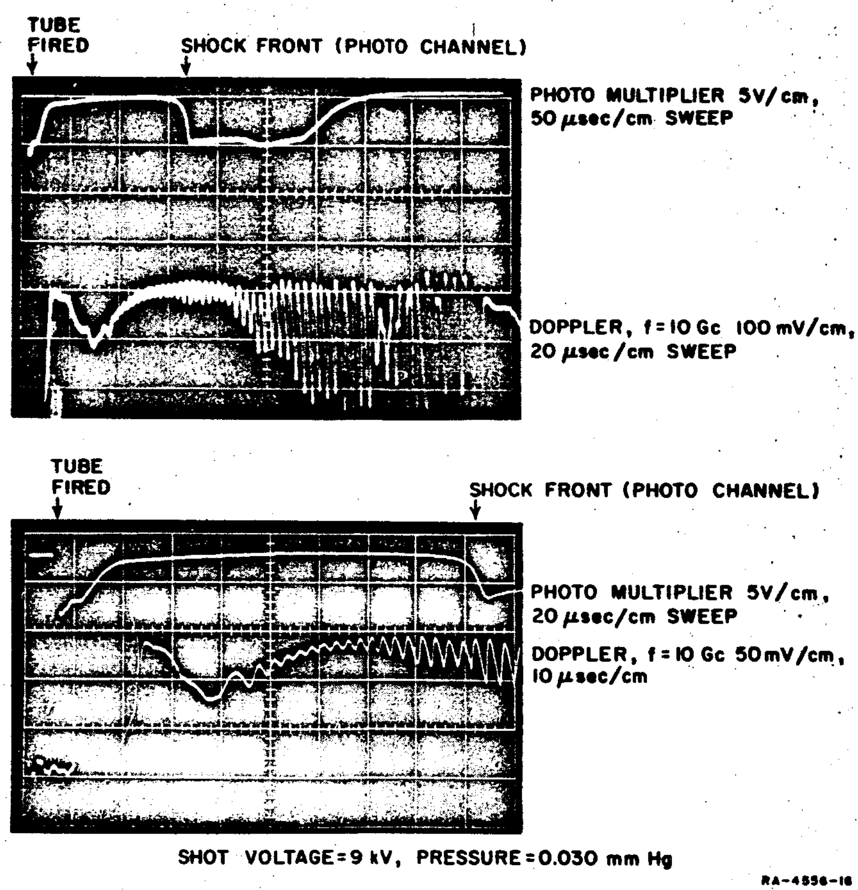


FIG. 9 TYPICAL DATA OBTAINED FROM THE DOPPLER SYSTEM

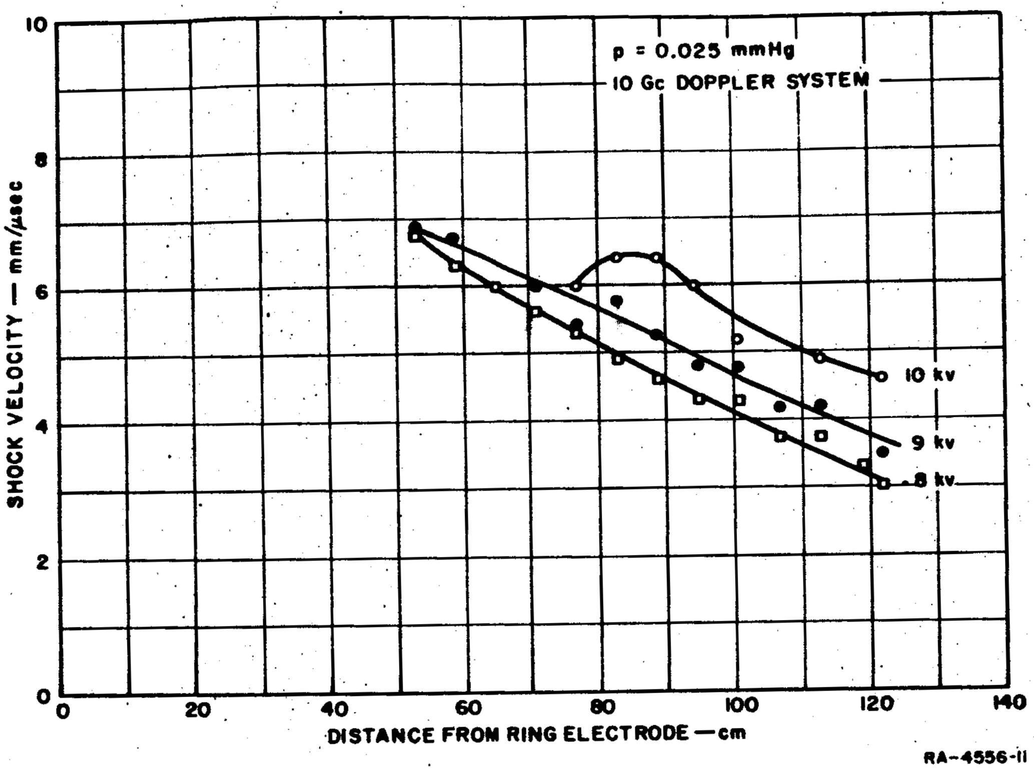


FIG. 10 SHOCK VELOCITY AS A FUNCTION OF POSITION FROM THE RING ELECTRODE AS DETERMINED FROM THE DOPPLER DATA

near the maximum for which measurements were possible. From measurements of the shock velocity with photomultipliers and probes, it is known that this is not the actual behavior of the shock velocity. Within about 20 cm after emerging from the discharge section, the shock begins to decelerate. Also, the actual velocities for the same shock voltages measured by the other techniques were much higher than those measured by the Doppler technique when the range was large, but the different techniques agreed quite well at shorter ranges.

We believe that the explanation for this phenomenon is to be found in the effect of the precursor ionization on the value of the speed of light in the medium. In order to interpret the Doppler frequency in terms of radial velocity it is necessary to know the velocity of light in the medium. The results shown in Fig. 10 assume that this is equal to 3×10^8 m/sec, its value in a vacuum. However, the presence of the precursor ionization, produced when the tube is fired, makes this assumption a poor one. When this ionization has relaxed to the point that the microwaves can penetrate it, there is still enough ionization present to alter the index of refraction in which the microwaves travel to less than 1. In a medium with an index of refraction less than unity, the velocity of light is greater than it is for a vacuum. Under these conditions, the Doppler frequency that is detected will be less than it would have been had the microwaves been traveling in a vacuum. As the precursor ionization relaxes, this effect becomes smaller and the Doppler frequency can be used to infer shock velocity, assuming propagation in a medium of index of refraction of unity. Thus, the measurements later in time are not affected by the precursor ionization and agree with the velocity as inferred from photomultiplier measurements.

This phenomenon is a serious limitation on the use of the Doppler technique of measuring shock front velocity in electromagnetic shock tubes, although it should not be a problem with pressure-driven tubes, since the precursor ionization is not present.

If the shock velocity is known from other techniques, the Doppler velocity can be used to determine the electron density into which the shock is moving. This is true because the Doppler frequency is affected only by the velocity of light in the medium in the vicinity of the moving scatterer. The limits of the vicinity are determined by the velocity and the time it takes to make a measurement of the Doppler frequency.

4. Probe-Sweeping Circuits

In order to determine both the electron density and temperature, it is necessary to have a complete double-probe characteristic. This is not strictly true if appropriate derivatives are obtained (rather than a complete current-voltage characteristic), but for an investigation of probe operation under conditions for which there is no theory, it is best to have the complete curve. Unusual phenomenon can then be most easily detected.

The electromagnetic shock tube provides a time-varying plasma, in which both the electron density and temperature are functions of time. In order to make measurements in a relatively fixed plasma, it was necessary to make measurements in times short compared to the time in which the plasma could change appreciably. Aside from the region right at the shock front, the plasma does not change appreciably in many microseconds. Thus, if the voltage applied to the probes was varied at a rate of the order of hundreds of kilocycles, the plasma would be a constant over one period. A higher frequency would be necessary if the shock front itself were to be studied. Since this study did not call for any particular interest in the shock front, it was decided that a sweeping voltage of a few hundred kilocycles would be adequate. As the study progressed, it became clear that a frequency of one hundred kilocycles was adequate. It was desirable to use the lowest frequency consistent with a fixed plasma in order to minimize the effect of stray capacitance between the leads to the probes. Due to the presence of this capacitance, there was an ac current even when there was no plasma. This formed a background current level against which the current that flowed when a plasma was present had to be read. Since with equal-area probes the maximum current that is measured is the ion saturation current (not the electron saturation current, which is much larger), the plasma appears as a relatively high impedance. For this reason it is desirable to keep the capacitive reactance to a maximum.

The measurements were to be made by comparing the results of two different probes under nominally the same conditions. Therefore, it was necessary to apply the sweeping voltage simultaneously to two different pairs of probes. Further, any coupling between the probes would confuse the results. Therefore, in order to isolate the probe circuits as much as possible, transformer coupling was used. The circuit is shown in Fig. 11. A sinusoidal voltage was applied to the input transformer from a Hewlett-Packard 200C generator. The transformer was wound with two identical secondaries, each of which fed a pair of probes. Aside from stray capacitance there was no coupling between the

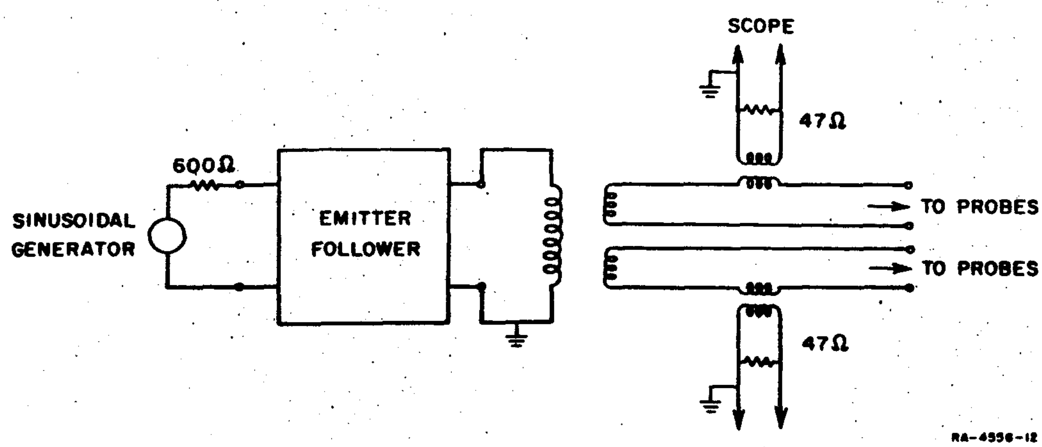


FIG. 11 SCHEMATIC DIAGRAM OF THE PROBE SWEEPING CIRCUITS

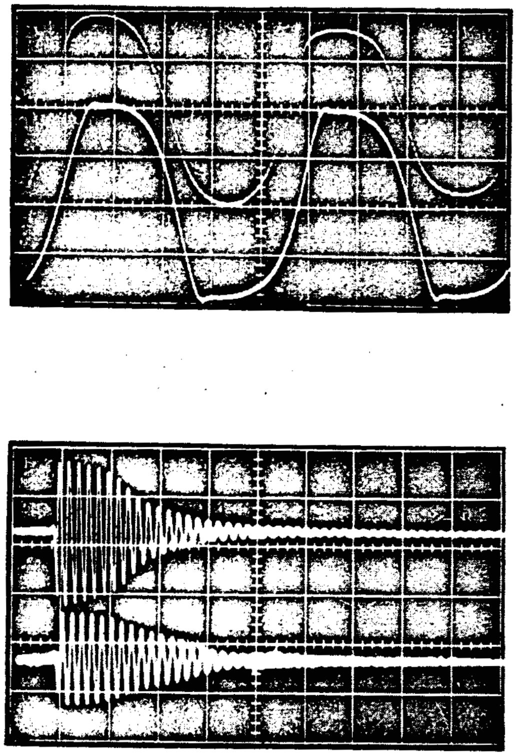
probes, so that there was no current flow from Probe 1 to Probe 3 or from Probe 2 to Probe 4. With direct coupling, this might have been a problem.

In order to keep the probes from becoming coupled through the oscilloscope ground leads, the current that flowed in each probe circuit was measured by coupling it through an output transformer. These transformers were terminated in 1% 47-ohm resistors. The voltage across these resistors was measured on an oscilloscope as a measure of the current in the probe circuit. The entire system was calibrated by placing known resistors across the probe terminals and measuring the voltage produced across the 47-ohm resistors when a given voltage was measured across the resistor between the probe terminals. Since the transformers were all 1:1 transformers, the current in the probe circuit was approximately equal to the voltage across the 47-ohm resistor divided by 47 ohms. The calibrations verified that this was true to a high degree of accuracy.

The frequency response of the transformers was checked by applying a 100 kilocycle square wave to the probe terminals and observing the waveform of the voltage across the 47-ohm resistor. Rise times of the order of a few tenths of a microseconds were observed. The square wave had rise times of this order so that it was concluded that the transformers introduced negligible distortion.

The output impedance of the signal generator was 600 ohms. When high electron densities were being measured, the impedance of the plasma was low enough so that when it was reflected into the primary of the input transformer an appreciable portion of the generator voltage appeared across the generator impedance. Thus, if the open-circuit generator voltage was 10 volts peak-to-peak, when a highly ionized plasma was present, the input voltage might drop to 5 volts peak-to-peak. In order to avoid this change of input voltage with load impedance, an emitter follower circuit was designed and built. When it was placed in series with the signal generator, it lowered the generator impedance to the point where the plasma conditions did not affect the input voltage. In this way it was possible to set the generator voltage under no-plasma conditions and be assured that the voltage remained the same when measurements were made with a plasma present. The emitter follower was capable of output voltages up to about 20 volts peak-to-peak. For accurate measurement the peak-to-peak voltage should be about $5\frac{kt}{e}$.

Measurements were made in two modes. In one mode the oscilloscope was set at a low sweep (say 100 microseconds/cm) and the scope triggered when the tube was fired. The signal generator was allowed to run freely. This mode gave an over-all picture of the probe characteristics throughout the entire shot, but the sweep time was so slow that individual cycles could not be used to measure temperature. In the other mode, the generator was still allowed to run freely, but the scope delay line was used to select a portion of the shot. The sweep time was then set at a higher rate than previously (say 2 microseconds/cm) so that only two cycles of the probe current was recorded. At this faster sweep time, enough detail of the individual cycles could be obtained to determine the temperature and electron density. Examples of operation under these two modes are shown in Fig. 12.



8 mil PROBES
20 mV/cm, 2 μsec/cm

50 mil PROBES
200 mV/cm, 2 μsec/cm
TIME DELAY = 350 μsec

8 mil PROBE
200 mV/cm, 50 μsec/cm

50 mil PROBE
2 V/cm, 50 μsec/cm

TIME DELAY = 100 μsec

p = 0.040 mm Hg
9 kV SHOT VOLTAGE
STATION—112 cm FROM RING
ELECTRODE

RA-4556-14

FIG. 12 PROBE CURRENT AS A FUNCTION OF TIME FOR TWO DIFFERENT SWEEP RATES

Since what is measured is the probe current as a function of time, it is necessary to translate the time axis into voltage. This is easily accomplished, since we know that the input voltage is varying sinusoidally at a 100-kilocycle rate. Further, at times near when the voltage crosses the zero axis, the voltage varies approximately linearly with time.

IV EXPERIMENTAL RESULTS

A. SHOCK TUBE REPEATABILITY AND UNIFORMITY

Before meaningful comparisons could be made between probes operating in the free molecular and continuum regions, it was necessary to determine whether results from shot to shot could be compared or whether the variation in the plasma parameters from shot to shot was larger than the phenomenon that were to be studied. Even more important, it was necessary to determine the uniformity of the plasma across the diameter of the tube. If there were large differences in the electron density and temperature from point to point across the tube, it would be impossible to make probe comparisons.

To this end, two sets of probes were made as identical as possible and placed in the probe mounting holes in the brass plate. The probes were made of 0.008-inch-diameter tungsten wire, 1/4-inch long. They were mounted 1/4-inch above the brass plate, with their axes parallel to the shock velocity. Probe data were taken for a variety of shock voltages, pressures, and time delays.

The results indicated that the saturation current measured at one probe could be as much as twice the saturation current measured at the other probe. There was no systematic way in which this ratio varied. On a given shot, either probe might read higher than the other. Long after the shock front had passed the probes, the saturation currents were generally within 20% of each other. This is reasonable, since any differences in electron density would be smoothed with time, due to diffusion.

Shot-to-shot variations of the saturation current at a given time delay could vary as much as a factor of four. This variation is probably due to the difficulty in setting the shock voltage precisely, and the variation with which the discharge strikes in the discharge section. The conclusions from these tests were that for all but the crudest tests, comparisons could not be used from shot to shot. The uniformity of the plasma over the one-inch probe-mounting distance long after the shock passage was generally quite good. Just at shock passage, comparisons to a factor less than 1-1/2 could generally be counted on, with uncertainties greater than 2 occasionally occurring.

Tests were also made of the radial distribution of electrons, so that the validity of the assumption of a slab model in interpreting the microwave system measurements could be evaluated. These tests were only rough checks, a great deal more data being necessary before the radial distribution could be known with the desired accuracy. But these tests were made to at least get some indication of the radial variation.

The tests were carried out by again using the nominally identical probes in the probe-mounting hole, but with one probe spaced 1/4 inch from the plate while the other probe was spaced 1-1/4 inches from the plate. Since the probes themselves were spaced 1-inch on centers, the results do not give a simple radial plot, but rather sample the plasma at two distances from the plate.

The results indicated that at 40 microns pressure for shock voltages of 9 and 12 kv, the electron density at a distance of 1-1/4 inches from the plate was larger than the electron density at a distance of 1/4 inch by about a factor of 1-1/2 at the time of shock passage. At later times, the electron density appeared approximately the same at both probes.

From this brief exploration of the radial distribution of the electron density, it was concluded that the microwave measurements could be imterpreted on the basis of a uniform slab model, with slab thickness equal to the distance between the brass plate and the shock tube wall, if accuracies within a factor of two were adequate. For more accurate measurements of electron density, it would be necessary to measure the radial distribution. Because of shot-to-shot variations, it would be necessary to measure the complete radial distribution on a single shot.

B. COMPARISON OF PROBES WITH DIFFERENT RADII

Now that some data had been gathered on the variations to be expected from shot to shot and with position across the tube, the comparison of probes with different radii could proceed. Differences in the electron density inferred from the two probes at times long after the shock passage could be attributed to differences in the manner in which the probes were operating, not to variations in the plasma itself. At times close to shock passage, differences in the probe characteristics within a factor of two might be due to differences in the plasma about the probes rather than differences in probe operation.

Measurements were made with a probe of 8-mil-diameter tungsten wire placed in one mounting hole and a probe of 50-mil-diameter tungsten wire placed in the other mounting hole. The current-voltage curves obtained from these probes were used to infer an electron temperature and electron density, using free molecular theory. Corrections were made for the difference between the physical area of the probes and the sheath area through which the current was actually passing. The sweep times had to be as fast as 2 microseconds per cm in order to read the data sufficiently accurately to obtain temperature information. Thus, for each shot, only about twenty microseconds of data were taken. In order to obtain results for different electron densities, the delay was adjusted so that data was taken at increasingly longer times after the shock passage. The plotted results thus represent the results of a large number of shots, each data point representing a single shot.

The results for a series of shots at 9 kv, at a pressure of 0.040 mm hg, and at a station 112 cm from the ring electrode are presented in Figs. 13 and 14. The data are plotted as ratios of the quantities inferred, from the 50-mil probe divided by the quantities inferred from the 8-mil probe.

Figure 13 shows the ratio of electron temperature inferred from the two probes at different times after the tube was fired. Shock passage occurred about 200 microseconds after the tube was fired. The arithmetic

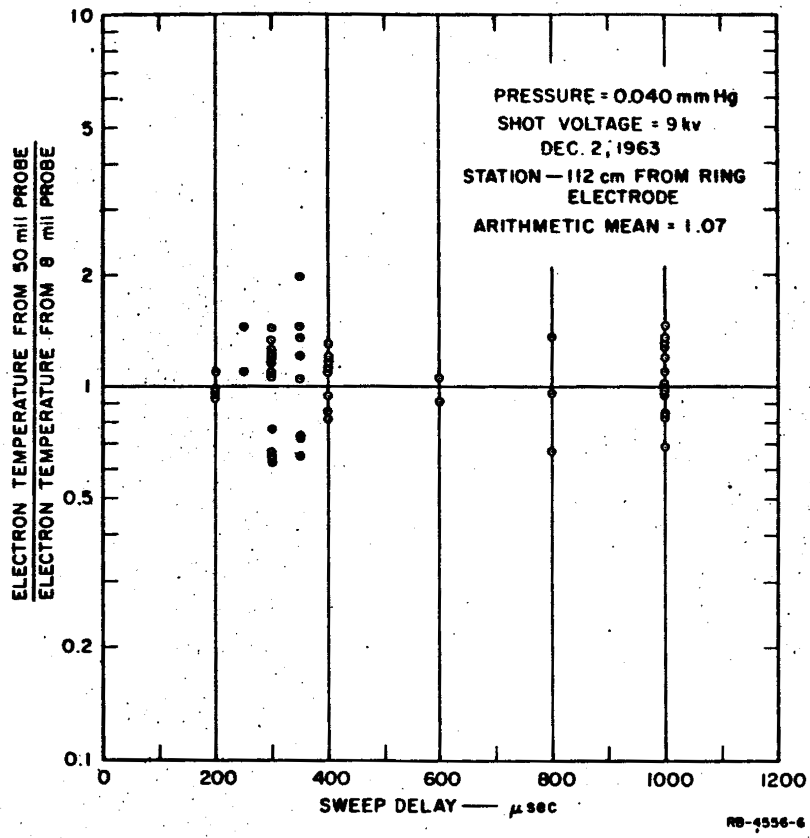


FIG. 13 RATIO OF ELECTRON TEMPERATURE INFERRED FROM THE 50 MIL PROBE TO THE ELECTRON TEMPERATURE INFERRED FROM THE 8 MIL PROBE AS A FUNCTION OF TIME AFTER FIRING

mean of the ratio is 1.07. This means that the two probes indicated the same temperature, on the average, within 7 percent. We conclude, therefore, that the measurement of electron temperature is not being distorted by the use of the larger probe. We assume that the variation in the ratio about the mean is due to variations in the measurement of temperature from the oscillographs and to actual variations in the plasma.

Figure 14 shows the results for the measurement of electron density. In this case the electron density inferred from the 50-mil probe is less than that inferred from the 8-mil probe. The arithmetic mean of

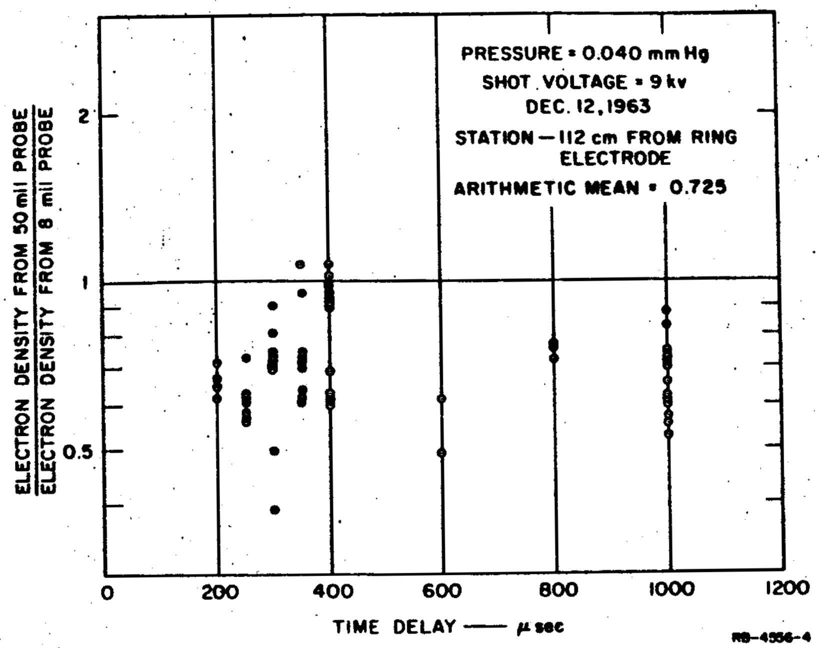


FIG. 14 RATIO OF ELECTRON DENSITY INFERRED FROM THE 50 MIL PROBE TO THE ELECTRON DENSITY INFERRED FROM THE 8 MIL PROBE AS A FUNCTION OF TIME AFTER FIRING

the ratio is 0.725. Although the lower readings from the 50-mil probe are definite, the difference between the two probes is too small to be considered as indicating the effect of using a probe that is comparable to a mean free path. The difference between the two probes is only 28%. This could be accounted for by small differences in the actual lengths of the probes from those that were used in the calculations. The ambiguity in the proper length of probe to use is due to the way in which the probe protrudes from the dielectric sheath that insulates the feed lines. Some of the sheath that surrounds the dielectric may overlap the probe and affect its current-collecting ability. Because of the different radii, this effect will be different for the two probes. Further, a small amount of contamination on the probes may decrease their current collecting ability.

From Fig. 2, the ion-neutral mean free path is about 25 mils at a pressure of 0.040 mm hg. The ion-electron mean free path is much longer for the electron densities that were obtained from the 9-kv shocks. Thus, the mean free path long after shock passage was about six times greater than the probe radius for the 8-mil probe, while it was about equal the probe radius for the 50-mil probe. The 8-mil probe was operating in the free molecular region, while the 50-mil probe was in a transition region between free molecular and continuum flow. The results seem to indicate that free molecular theory gives good results for electron density and temperature even for probe radii as large as one mean free path.

In the shock front, the gas density is about an order of magnitude greater than ambient, so that the mean free path is an order of magnitude less than ambient. Thus, in the shock front the 8-mil probe is in transition flow, while the 50-mil probe is well into continuum flow. The results of Figs. 13 and 14 show that both probes measure comparable electron densities and temperatures even at the time that the shock passes. This would seem to indicate that even when the mean free path is 1/10 the probe radius, free molecular theory is still adequate. However, because of the uncertainty with which the state of the gas is known in the electromagnetic shock tube, it is advisable not to lean too heavily on data obtained in the shock front unless the gas parameters are measured at the same time.

In order to check the probes further into the transition region, measurements were made at a higher pressure. The results for measurements at 0.200 mm hg at a shot voltage of 11 kv are similar to those at 0.040 mm hg and 9 kv. The arithmetic mean of the ratio of the electron temperature inferred from the 50-mil probe compared to that from the 8-mil probe is 0.995. The two probes measure essentially the same temperature. The arithmetic mean of the electron density ratios is 0.59. The 50-mil probe reads a somewhat lower electron density than the 8-mil probe.

At 0.200 mm hg, the ambient mean free path is about 5 mils, so that the 8-mil probe is in the transition region while the 50-mil probe has a radius five times the mean free path. Since the 8-mil probe is not operating under free molecular conditions, it cannot be assumed that the results obtained from it are correct. The measurements made at 0.040 mm hg showed that the error in electron density incurred by interpreting a probe operating at a ratio of probe radius to mean free path of one, is less than 30%. Therefore, the 8-mil probe operated at a pressure of 0.200 mm hg cannot be in error by more than 30%. If it is assumed that the 8-mil probe at 0.200 mm hg is reading 30% low, then the 50-mil probe at this same pressure is reading about 50% low in electron density. This would seem to be an outside number for the error introduced by operating the probe such that the ratio of probe radius to mean free path is five. A more accurate number for this error could be obtained by using a probe with a radius sufficiently small to be operating under free molecular conditions at 0.200 mm hg. Time did not allow this to be done.

The range of electron densities measured in these experiments was about 5×10^{10} to 5×10^{12} electrons/cc.

In Fig. 15 the temperature inferred from each probe is plotted as a function of time. As would be expected, the temperature is a maximum at the time of shock passage (200 microseconds) and decreases with time. The increase in temperature at 1000 microseconds after the tube is fired is due to the reflected shock reaching the observation station at this time and heating the gas.

Equal-area probes are quite susceptible to erroneous temperature measurements if the electron energy distribution is not Maxwellian. This is because only the high-energy tail of the distribution is sampled by the probes. The bulk of lower-energy electrons never reach the probes. Thus, a deviation from the Maxwellian distribution in the high-energy portion of the distribution can introduce errors into the temperature measurement.

A probe consisting of electrodes of unequal areas will sample a larger portion of the distribution than an equal-area probe. If the

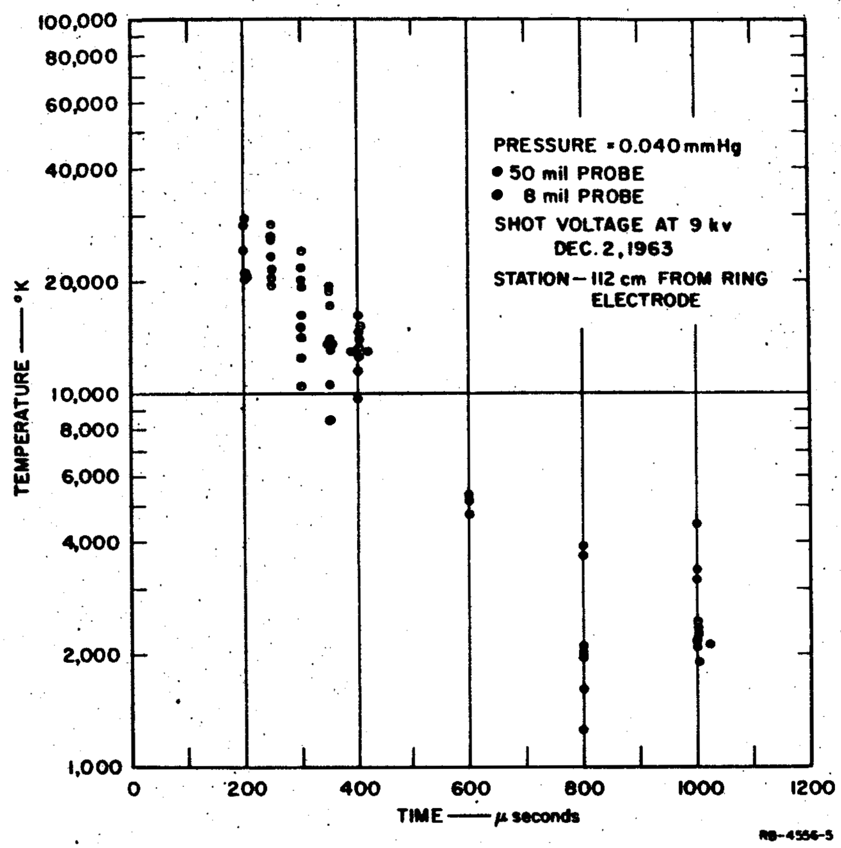


FIG. 15 ELECTRON TEMPERATURE INFERRED FROM EQUAL AREA PROBES AS A FUNCTION OF TIME AFTER FIRING

ratio of electrode areas is made large enough, it will be possible to bias the probe so that the entire random electron current is collected so that a good measure of the distribution function can be made.

In order to determine if the temperatures that were measured were in error because only the high-energy portion of the distribution was being sampled, an unequal area probe consisting of an 8-mil wire 0.25-inch long wire and a 50-mil wire 0.50-inch long was constructed. This allowed a considerably larger portion of the distribution to be sampled.

The results of the temperature measurements with this probe are shown in Fig. 16. The shot conditions are the same as those used with

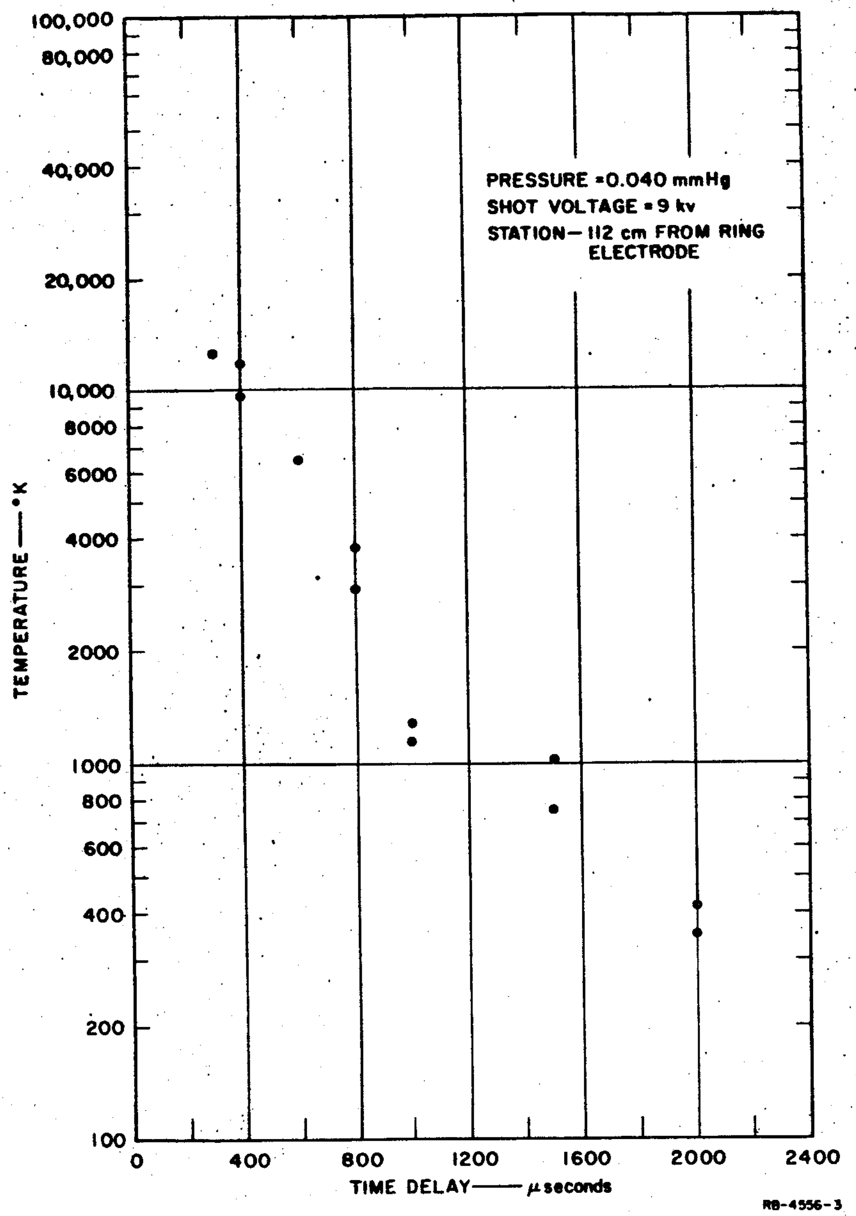


FIG. 16 ELECTRON TEMPERATURE INFERRED FROM AN UNEQUAL AREA PROBE AS A FUNCTION OF TIME AFTER FIRING

the equal area probes. Unfortunately, there was not sufficient drive voltage to get measurements right at the shock passage, but at later times (300 to 400 microseconds) the temperatures measured by the unequal area probes were somewhat lower.

In order to reduce the shot-to-shot variation, it would be desirable to use an equal-area and an unequal-area probe at the same time. As the results stand now, it is uncertain whether the high temperatures measured by the equal-area probes are accurate measurements of the electron temperature or whether they are in error due to deviations from the Maxwellian distribution. Further measurements would clarify this point.

C. COMPARISON OF MICROWAVE MEASUREMENTS WITH PROBE MEASUREMENTS

Probes may give erroneous results for a number of reasons that do not pertain to the microwave measurement. This is mainly due to the fact that the probes are in contact with the plasma while the microwave system is not. For this reason, the microwave system may be used as a check to ensure that the probes are operating properly. But the microwave system was not used extensively for two reasons. Quantitative comparisons between the two systems to an accuracy greater than a factor of two are questionable without detailed information on the electron spatial distribution. Since this would require a great deal of instrumentation, it was decided to use the microwave system only as a check to a factor of two. Secondly, because the system operated at X band, electron densities greater than 10^{12} electrons/cc attenuated the signal to such an extent that the system could not be used. However, for all but the lowest shock voltages, electron densities greater than 10^{12} electrons/cc were obtained in the vicinity of the shock front and for about 100 microseconds later. Thus, the microwave system was useless for checking the probe data in the vicinity of the shock front on all but the weakest shocks.

Comparisons were made between the electron density inferred from equal-area probes and the X-band microwave system at pressures of 0.040, 0.140, and 0.200 mm hg. The results were similar in all cases. The electron density inferred from the two techniques agreed well within a factor of two. In a series of shots at a pressure of 0.140 mm hg, the arithmetic mean of the ratio of the electron density inferred from 8-mil probes to the electron density inferred from microwaves was 0.86. It was thus concluded that the probes were operating properly, with none of the anomalies to which probes are liable.

A final reason for not relying on comparison between microwave and probe measurements to check probe theory is that the ion species that are collected is not known for certain. It may be NO^+ or it may be N^+, and it may be one or the other, depending upon the pressure or shock voltage. We have assumed that we were collecting NO^+ ions throughout this report but if this assumption is wrong the values of the electron density would be too high by about 40%. In comparing probes, the ion mass, and hence the particular species is insignificant, while in comparing probes to microwaves it can introduce a 40% error.

D. VELOCITY EFFECTS

If it is assumed that the shape of the sheath is not affected by the directed velocity and that there are no collisions between the particles, it is possible to derive the current that will be collected by a probe in a flowing plasma. The derivation has been carried out for a cylindrical probe by Mr. Guthart of our laboratory, with the results shown in Fig. 17. V_0 is the directed velocity of the plasma and $\dot{c}$ is a measure of the velocity with which the ions randomly enter the sheath, taking into account the increase in their velocity because of the electric field that extends beyond the sheath. When the directed velocity is much less than the random ion velocity, the current that is collected is the same as would be collected if the plasma were stationary. When the directed velocity is much larger than the random ion velocity, the current increases linearly with the directed velocity and is equal to the product of the electron flux, nV_0, times the projected area of the cylindrical probe, $2a\ell$ (a is the probe radius and ℓ the probe length).

Measurements were made to verify this theory, especially in regions where the mean free path is comparable to the probe radius. The measurements were performed by placing equal-area probes in the two mounting

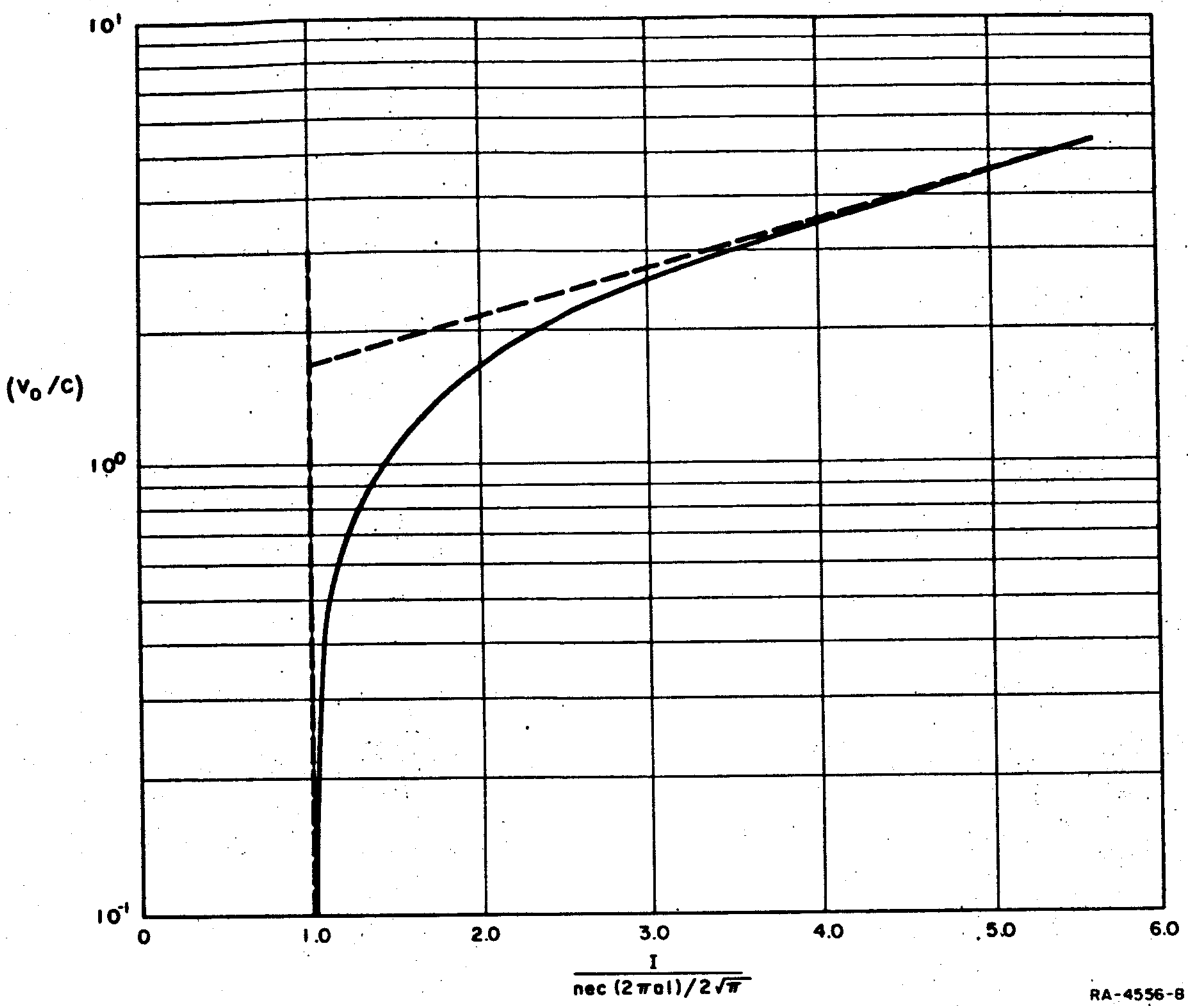


FIG. 17 RATIO OF DIRECTED TO RANDOM VELOCITY AS A FUNCTION OF THE RATIO OF THE CURRENT COLLECTED BY A PROBE PERPENDICULAR TO THE DIRECTED VELOCITY TO THE CURRENT COLLECTED BY A PROBE PARALLEL TO THE DIRECTED VELOCITY

holes in such a manner that the electrode axis of one probe was parallel to the directed velocity, while the electrode axis of the other probe was perpendicular to the directed velocity. The probe that was oriented parallel to the directed velocity should only pick up current associated with the random ion velocity, while the other probe should pick up current due to both the random ion and the directed velocity.

The random ion velocity is determined from the electron temperature, which in turn is determined from the probe current-voltage characteristics. The directed velocity is measured by the Doppler system. Thus, the ratio of I/I_o that is predicted from the theory can be checked against the measured value of this ratio.

The probe data for two different shot voltages at a pressure of 0.040 mm hg is shown in Fig. 18. The upper figure is for 9 kv while the lower is for 12 kv. Assuming that the temperature is 11,000 °K, which is the value measured with the unequal-area probe, the measured and predicted values of current ratio are

Shot Voltage	I/I_o -Theoretical	I/I_o -Measured
9 kv	1.6	1.8
12 kv	1.96	2.05

The agreement between the theoretical and measured values is within about 10%. This indicates that for the experimental conditions that were used the simple theory is adequate. Additional work remains to be done at higher pressures where collisions will become important and the flow field is no longer free molecular.

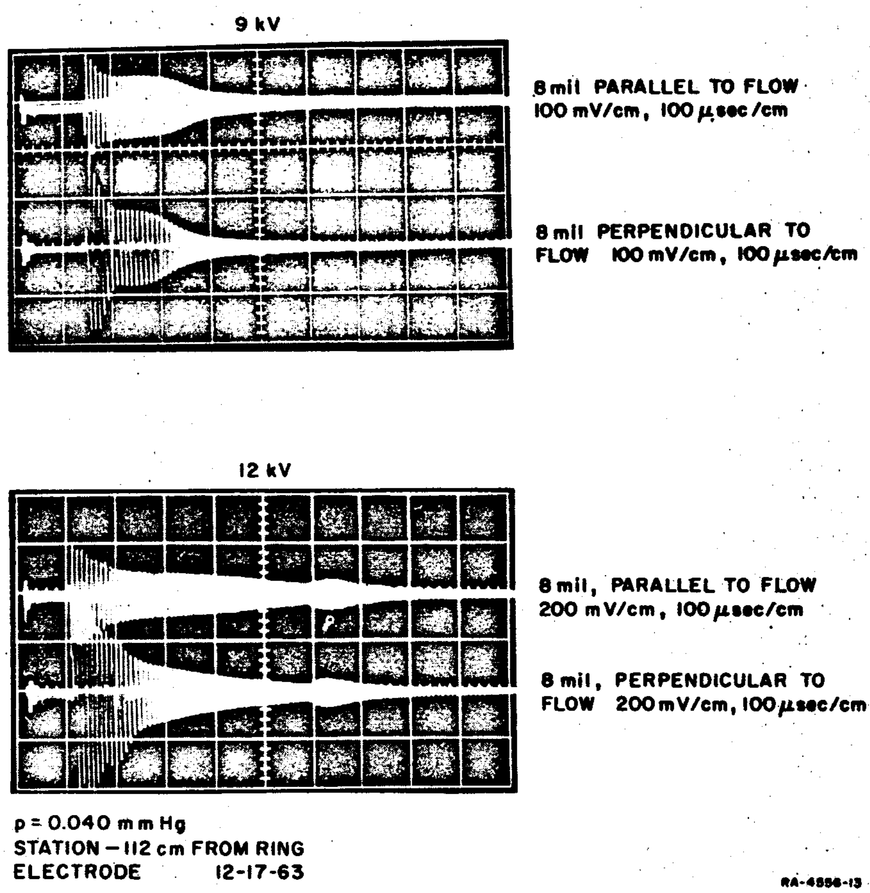


FIG. 18 PROBE CURRENT AS A FUNCTION OF TIME FOR PROBES PERPENDICULAR AND PARALLEL TO THE DIRECTED VELOCITY

V CONCLUSIONS

A technique for obtaining complete current-voltage characteristics in times short enough to be useful for measurements in shock tubes has been developed and checked against microwave measurements.

The experimental results presented in the previous section showed that both the electron temperature and electron density for the 50-mil probe checked these same parameters for the 8-mil probe. If the probe were disturbing the plasma, it would be expected that the properties inferred from the two probes would differ by a greater amount than was observed. It is concluded that the electrostatic probe can be used to obtain significant measurements even when the mean free path is smaller than the probe radius. Because the mean free path is not known accurately, it is uncertain precisely how much smaller the mean free path was then the probe radius. At 0.200 mm hg, the calculated value of the mean free path was one-fifth the radius of the 50-mil probe.

There was no external check on the values of the electron temperature, but the electron densities were checked with an X-band microwave system. The agreement between the microwave transmission measurements and the probe measurements is sufficiently good to establish that the probes were correctly measuring the electron density.

A simple theory to account for the change in current collection under conditions where the probe is in a flowing plasma was experimentally verified in the critical transition region between the case where the flow velocity is negligible and the case where it is dominant.

It is clear that as the mean free path is made successively smaller, there will come a point where free molecular theory will be inadequate. For the range of parameters covered in this study, that point was not reached. Further work is needed to find the point at which the free molecular theory is no longer adequate and to gather experimental data on the manner in which the current-collecting characteristics of probes operating under these conditions is changed.

Now that the instrumentation has been developed, the rapid-fire capabilities of the electromagnetic shock tube are not needed as much as a plasma with theoretically better-defined properties as is obtained in a pressure-driven shock tube. With the pressure-driven shock tube, measurement of the velocity and initial pressure will allow the equilibrium electron density, temperature, and ion species to be calculated. A pressure-driven shock tube will shortly be available at this laboratory. It is planned that this investigation will continue using the pressure-driven shock tube.

Although this study did not have enough time to pursue the problems as far as would be desirable, it has been demonstrated that reliable measurements of electron density and temperature can be made with Langmuir probes even when they are immersed in plasmas that are not strictly operating in the free molecular region. Even if they were unusable at altitudes lower than those corresponding to the free molecular region, they can provide engineering estimates of two parameters of great interest, the electron density and temperature.

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